

Radial flow afterburner for event generators and the baryon puzzle

E. Cuautle and G. Paic

Departamento de Física de Altas Energías
Instituto de Ciencias Nucleares,
Universidad Nacional Autónoma de México, México D.F., C.P. 04510.
E-mail: ecuautle@nucleares.unam.mx, guypaic@nucleares.unam.mx

Abstract. A simple afterburner to add radial flow to the randomized transverse momentum obtained from event generators, PYTHIA and HIJING, has been implemented to calculate the p/π ratios and compare them with available data. A coherent trend of qualitative agreement has been obtained in pp collisions and in $Au + Au$ for various centralities. Those results indicate that the radial flow does play an important role in the so called baryon puzzle anomaly.

(Some figures in this article are in color only in the electronic version)

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1. Introduction

The study of heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) has brought about very strong evidence for the creation of a very high energy density, low baryon chemical potential, medium which cannot simply be described in terms of hadrons [1]. Prominent demonstrations of this new medium created are: parton energy loss, evidence for very rapid thermalization of the hot plasma created in collisions from the measurement of azimuthal flow, and abundant production of baryons compared to the case of the some yields observed in proton proton collisions. The first effect we mention *i.e.* the parton energy loss in the hot plasma results in a suppression of the yield of high p_t ($p_t > 4 \text{ GeV}/c$) mesons by a factor of ≈ 5 compared to the one measured in pp collisions. This is quantified by the parameter R_{AA} given by

$$R_{AA} = \frac{\left(\frac{dN}{d^2p_T dy}\right)^{AA}}{T_{AA}(b)\left(\frac{dN}{d^2p_T dy}\right)^{pp}} \quad (1)$$

and/or the measurement of the disappearance of “away side” jets. $T_{AA}(b)$ is the overlap function between the two nucleons, as function of the impact parameter, b . The measurement of the same ratio for baryons (p , \bar{p} , Λ and $\bar{\Lambda}$) have brought a surprise: the value of R_{AA} was completely different from the one observed for pions indicating a much lesser apparent suppression or, what is more probable, an increase in the baryon production in the range where the excess is observed. This effect was not predicted by theory contrary to the parton energy loss and the azimuthal flow, and up to date does not have a completely satisfactory explanation. This somewhat anomalous behavior of the baryon production is called the baryon puzzle and refers to the p/π^+ and \bar{p}/π^- ratios measured in the heavy ion collisions and even in pp collisions.

The studies of particle production as a function of p_t , in the momentum regions where identification is possible at RHIC, exhibit the following behavior: the p/π^+ and \bar{p}/π^- ratios increase with p_t up to $\approx 2 \text{ GeV}/c$ and then start to decrease for higher p_t in both pp [2] and $Au + Au$ [2, 3, 4] collisions, reaching a value which corresponds to the fragmentation value observed in e^+e^- collisions for quarks and gluons [5].

The spectra at $p_t < 2 \text{ GeV}/c$ have been observed to follow a m_t [6] and x_T [2] scaling, consistent with a transition between soft and hard processes at around $p_t \approx 2 \text{ GeV}/c$. The surprise lies in the fact that one would expect a ratio that does not exceed the fragmentation value *i.e.* ≈ 0.2 as observed in e^+e^- collisions, while in the experiment the ratio rises up to more than one!

In the literature two possible explanation are prominently put forward:

- the hydrodynamical approach [7, 8, 9] where one assumes a local thermal equilibrium of partonic/hadronic matter at an initial time, describing the space-time evolution of thermalized matter by solving the equations for energy-momentum conservation in the hydro picture. Another model, where the radial flow and the size of the system of emitting particles are taking into account [10], can describe the proton to pion ratio for different centralities.

The hydrodynamical picture has been used to explain the broad features of the increase in the baryon/meson ratio with limited success by Kolb and Heinz [11].

- A large class of models called generically "coalescence" where the particle species ratios observed in the intermediate p_T regime (2-6 GeV/c) of heavy ion collisions are explained by a collective production mechanism, namely recombination or coalescence [12]. In most coalescence models hadrons are assumed to form from essentially collinear partons. The parton overlap function is sometimes simply assumed to be a delta function, or at best in some cases small finite transverse widths have been used, assuming an x_T distribution like one expects to see in the final state hadron, such that the partons do not have to undergo a change in momentum when forming a hadron. Although the coalescence models have been accepted, they do not provide a satisfactory response to many questions [13].

Furthermore in our opinion there also is a fundamental contradiction between the fitting of the spectra with the coalescence approach which involves also some flow contribution and the thermal analysis where, by a simultaneous fit to the slopes of pions, kaons and protons one extracts the temperature and the corresponding flow [14]. Since the coalescence approach **does change** the proton slope with respect to the one of the mesons even in absence of flow, the temperature–flow analysis should be reconsidered if the coalescence model is to be accepted. Recently, experimental data measured at two different energies also indicate that the trend of the coalescence models do no fit the data [15]

It is a fact that none of the models have been tested in a wide centrality and energy range or with different projectiles, so that the success of this approach should be questioned.

We present a toy model that illustrates the possibility to reproduce the observed ratios for p/π^+ using a model to incorporate the flow in the existing event generators. The aim is to demonstrate that the radial flow, as claimed in hydro calculations, does have a considerable influence on p/π^+ ratios in a wide range of centralities starting from pp collisions. One might ask why are we including the proton collisions in these considerations - knowing that it is difficult to expect flow in so light a colliding system. We include the pp collisions because in the conventional radial flow analysis of STAR [16], making a simultaneous fit to the slopes of pion, kaon and proton spectra an "*equivalent flow*" of $\approx 0.2c$ is found. The measured value is of course much smaller than the one obtained in the most central $Au + Au$ collisions where the value of flow reaches $\approx 0.6c$.

The remainder of this work is organized as follows: in section 2, we give a brief description of the event generators, the section 3 describes our toy model of flow used to describe experimental data. In section 4, the results of our model and their comparison to experimental $Au + Au$ and $p + p$ results are presented. Finally some conclusion are drawn in section 5.

2. The event generators

The main tool of comparison of the measured with the existing knowledge is compiled in the so called event generators. Among them the most prominent is the PYTHIA[17] generator for the proton-proton collisions and the HIJING [18] generator for the heavy ion collisions. We should mention that even proton-proton collision can be studied using HIJING. The version 6.2 of PYTHIA, does not reproduce the proton to pion ratio [2] with its default parameters. The possibility to improve the situation by including the Leading Order(LO) and Next to Leading Order (NLO) corrections which are implemented in PYTHIA by the so called K-factor, has been explored. The requirement of a K-factor may indicate collective phenomena in pp collisions as in heavy ions data [19]. The K-factor as function of the energy has been extracted [9] together with other phenomena as energy loss for hard partons and temperature effects to explain the p_t spectra. Those studies indicate that while the pion spectra can be described with the default PYTHIA settings, (i.e. QCD processes at leading order) the proton spectra require the inclusion of a K-factor [19]!! (QCD processes with higher order corrections). Hence it is not possible to reach a consistent reproduction of the experimental data. The HIJING generator dedicated to heavy ion reactions does not reproduce the proton spectra in a similar way as PYTHIA. One has to add that neither of them includes the radial flow in the simulation, an important issue to describe results of heavy ions collisions.

We use the PYTHIA 6.3 generator with the popcorn baryon production mechanism. One can change parameters in the event generator, like the fragmentation function, and/or the hadronization mechanism. Recently it has been shown [20] that the differences in the proton/pion ratio at 200 GeV among different baryon production mechanisms are not very large so that we limit ourselves to the use of the popcorn hadronization mechanism in the PYTHIA generator - the one that is expected to give the best conditions for proton production. The HIJING 1.32 event generator has been used to generate $Au + Au$ and pp events, with default values of the parameters, for instance, including partonic energy loss, shadowing effects, among other phenomena. The pp collision with HIJING was generated with the default set of parameters.

3. Radial flow: our model

The radial flow is understood as representing the azimuthally symmetric collective aspects of the interacting hadronic medium [14], depending on the collision energy. The relevant observable to study the radial flow is the transverse momentum of the particles. For each particle, the random thermal motion is superimposed onto the collective radial flow velocity. Consequently, the invariant p_t distributions depends on the temperature at freeze out, the particle mass, and the velocity profile of the flow. The experimental data on radial flow at RHIC indicate that the kinetic freeze out temperature and the

observed flow are anti-correlated. The temperature decreases with centrality while the flow velocity increases [16, 20, 21]. From the most peripheral to the most central the flow for heavy ions collisions rises from $\approx 0.3c$ to $\approx 0.6c$.

We propose to introduce radial flow, to event generators as follow: in a first step we generate *flow-free* pion and proton spectra using an event generator to produce particles. We are assuming that a fireball, thermalized, and expanding was created in the collision. The expansion produces an additional momentum to the one created in the collisions using event generators. This contribution we call momentum of the radial flow $p_{t,f}$ given by $p_{t,f} = \gamma m \beta$, where γ is the Lorentz factor, β is the profile velocity and m is the mass of the particle under consideration. This radial component is generated in a random way in the transverse plane and is added vectorially to the transverse momenta produced by the generators, supposed not to contain flow. Once the vector sum is achieved, the transverse momentum p_t , of each particle generated includes now the radial flow. Then we can select the pions and protons and estimate the ratio comparing the results with and without flow versus experimental data.

The radial flow described above can be added to any event generator in order to compare among them and with the experimental data.

4. Results from our model versus data

The flow contribution considerably alters, as expected, the shape of the momentum spectra in the range 0 to ~ 4 GeV/c. The Fig. 1 represents a typical momentum spectrum for pions (left) and protons (right), obtained for central $Au + Au$ collisions with a velocity profile of the flow, $\beta = 0.5c$. In the same figure we show the PHENIX spectra [3] to show the degree of agreement between the spectra obtained with our model and data. Spectra for pp collisions using HIJING or PYTHIA shown in the Fig. 2 indicate that there are notable differences above 1 GeV/c, between the two generators. The differences are probably due to the parton distribution functions used and/or the fragmentation functions.

4.1. $Au + Au$ collisions at 200 GeV

Fig. 3 shows the results of our calculation including the flow in the generator, for the proton to pion ratio for $Au + Au$ collisions, compared to two experimental results, PHENIX [3] and STAR [15] for the most central collision. We also plotted the results without flow ($\beta = 0.0c$), to illustrate the importance of the flow the contribution to the ratio. The other centralities are also reasonably described using lower flow parameters, following the experimental results, as shown in Fig. 4. Without trying to get the best fit, the distributions show a qualitative agreement with the experimental results with a rise and a subsequent decrease of the ratio at p_t values from $\approx 2.5 - 3$ GeV/c onwards, for the three different centralities.

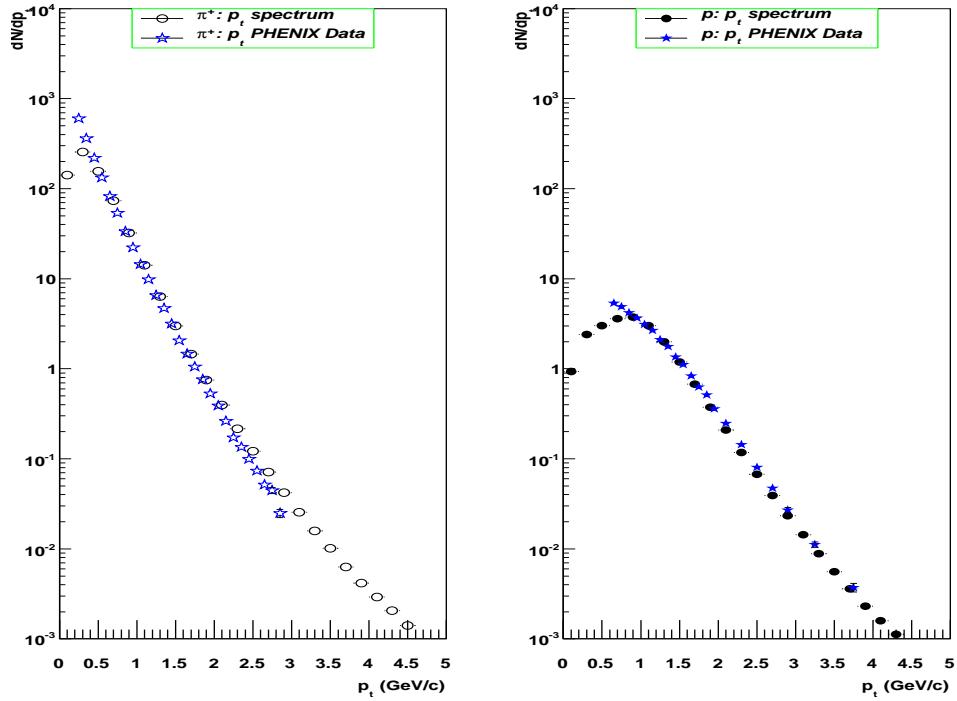


Figure 1. p_t spectra for pions (left) and protons (right) obtained applying the afterburner to $Au + Au$ central collisions generated by HIJING with a flow of $0.5c$.

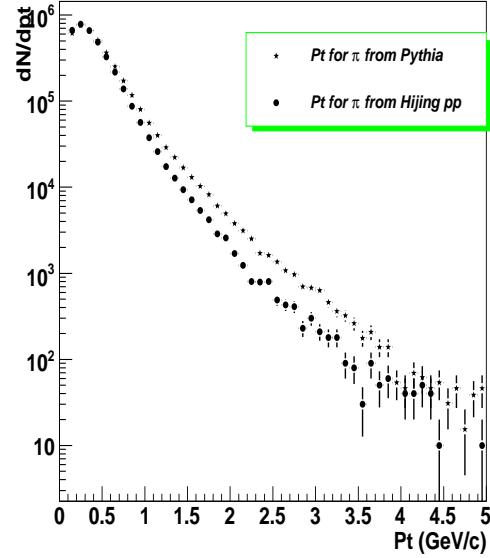


Figure 2. p_t spectra of pions as, generated for pp collisions with PYTHIA and HIJING event generators.

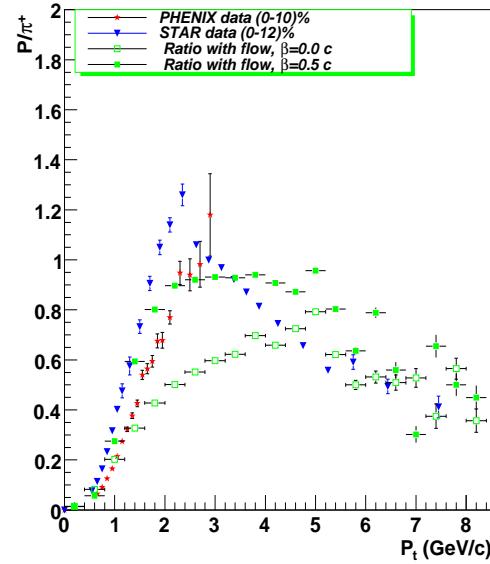


Figure 3. Proton to pion ratios obtained with the present model with and without flow, compared to data from PHENIX and STAR for most central collisions.

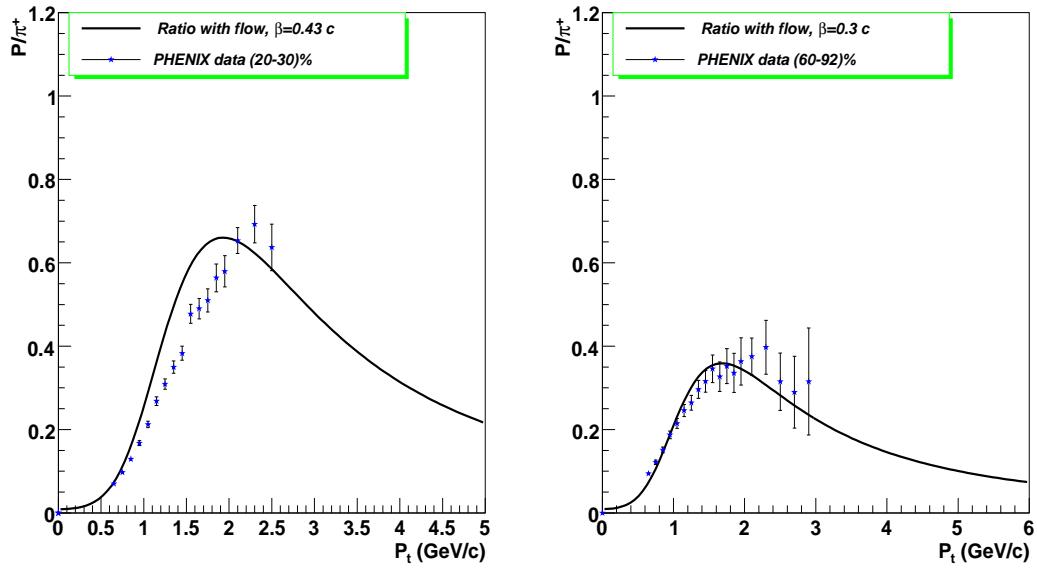


Figure 4. Proton to pion ratios obtained with the present model compared to data at two different centralities. The data are from PHENIX. The solid lines were obtained as the ratio of the fits to the simulated proton and pion spectra.

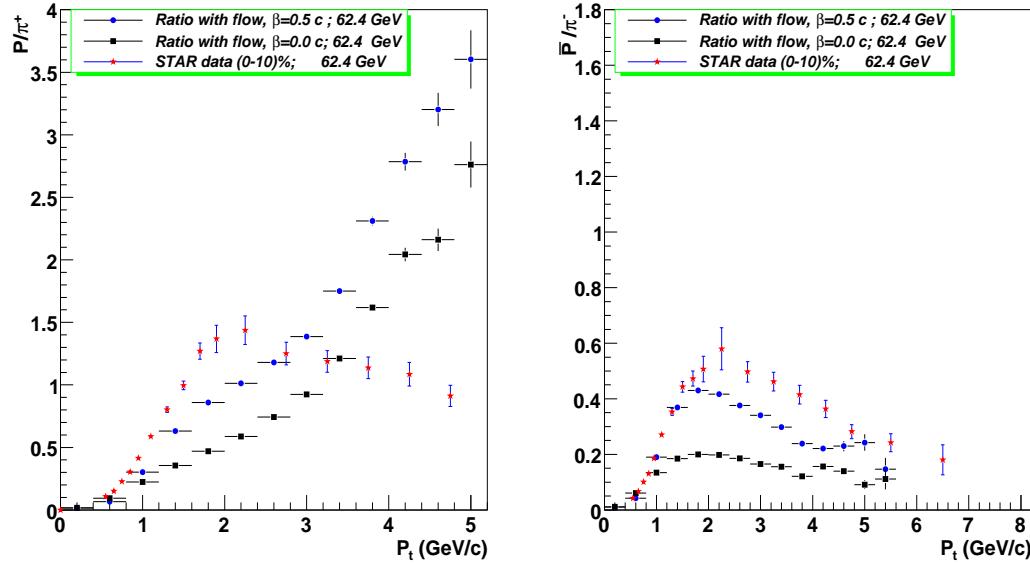


Figure 5. Proton to pion ratio from our model compared to central $Au + Au$ data at 62.4 GeV. The left part shows the results for p/π^+ while the right part shows the \bar{p}/π^- ratio.

4.2. $Au + Au$ collisions at 62.4 GeV

The data for protons at 62.4 GeV are difficult to analyze using HIJING. The HIJING generator at this energy, namely, overestimates grossly the proton production with respect to pions. This is due, in our opinion, to the fact that HIJING overestimates the contribution of valence quarks at these momenta thus grossly overestimating the proton production compared to the antiproton one, in the same way as it underestimates the \bar{p}/p ratio at these momenta. In the left part of the Fig. 5, we show the results of the HIJING predictions of p/π compared with and without the afterburner versus data. The results are completely different for anti-proton to pion ratio. The right part of the Fig. 5, show the \bar{p}/π^- data of STAR[15] with the HIJING predictions with and without afterburner. It is visible that the two predictions are completely different and that the afterburner again qualitatively reproduces the data although they suggests perhaps a somewhat larger flow. Let us note that the trend of our model is to predict the position of the maximum ratio at lower momenta than at 200 GeV in agreement with the data, while the coalescence models used in ref [15] show an opposite behavior.

4.3. pp collisions

The fact that even the ratios obtained in pp collisions cannot be satisfactorily explained with current generators as discussed by [2], prompted us to apply our model to them since the experimental analysis of the spectra in pp yields a value of $0.2c$ like in the case of peripheral $Au + Au$ collisions. We show in Fig. 6 the results obtained for

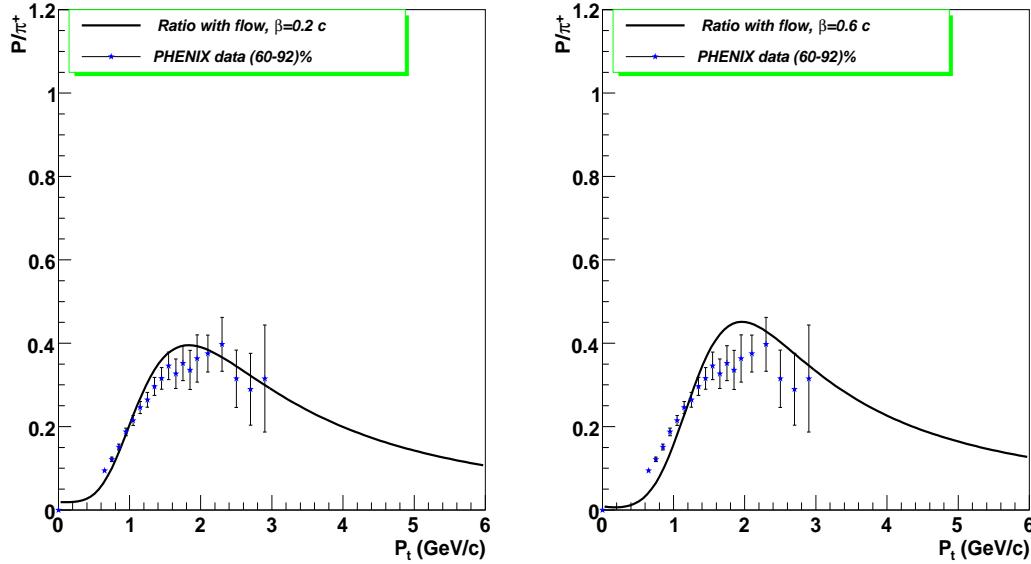


Figure 6. Proton to pion ratio from HIJING compared to peripheral $Au + Au$ data (left). The same data compared with PYTHIA generation and flow $0.6c$ is shown in the right. The solid lines were obtained as the ratio of the fits to the simulated proton and pion spectra.

the very peripheral - quasi pp like collisions using our afterburner one with HIJING (left) and one with PYTHIA (right). We find that PYTHIA requires a very large flow to fit the data while HIJING with a moderate flow similar to the one extracted from the experiments, fits reasonably well. This illustrates that the ratio depends crucially on the "initial spectrum", as discussed in section 2 (fragmentation functions, parton distribution functions, etc.). Also it should be mentioned that the HIJING event generator implements the nuclear effects like shadowing, energy loss, etc. even in peripheral collisions.

Results from STAR [2] pp collisions have been compared with HIJING events. In Fig. 7 we show this ratio. As in the case of peripheral data a good agreement is achieved incorporating the radial flow to the HIJING spectra, albeit the flow used is somewhat larger than the one found experimentally.

5. Conclusions

We have introduced radial flow in existing event generators (PYTHIA and HIJING) via an afterburner. The flow parameters that fit reasonably well the experimental results both in the proton to pion ratio and the p_t spectra are very close to the ones extracted from experiments in a thermal analysis. The success in reproducing qualitatively the data in a wide range of centralities, and in a large range of transverse momentum indicates that the presence of radial flow should be taken in consideration in any attempt to explain the so called proton puzzle.

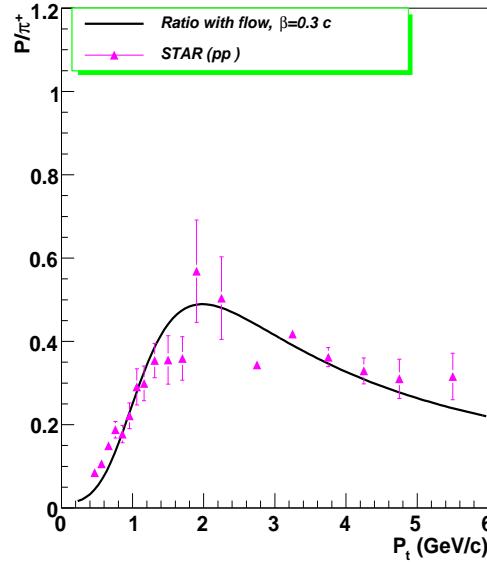


Figure 7. Proton to pion ratio from pp collisions using HIJING, compared to pp data from STAR experiment. The solid line was obtained as the ratio of the fits to the simulated proton and pion spectra.

In the present work we did not try to reproduce in details the ratios experimentally observed for two reasons; first the systematical and statistical errors of the experimental results and second as has been shown the “initial condition” of the generator have influences on the shape of the spectra leads to difference in the results after implementation of the radial flow.

The inclusion of a flow in pp reactions is not justified in terms of an expanding thermal system, but since the analysis of the pion kaon and proton spectra do yield something that may be termed ”flow” we can perhaps infer that the outward motion of jets produces an effect which does modify the hadron spectra in pp collisions.

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